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Association Between Tail Substorm Phenomena and Magnetic Separation Distortion

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VICE PRESIDENT
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Engineering and Technology Group

THE AEROSPACE CORPORATION
El Segundo, California

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NOTE

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Association Between Tail Substorm Phenomena and Magnetic Separation Distortion

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Important geomagnetic-tail phenomena have been observed to occur in association with substorm expansion phases. Often attributed to the systematic development and movement of a substorm neutral line, these phenomena include plasma sheet thinning and expansion, magnetic field stretching and dipolarization, particle injections, and outward and earthward plasma flows. It is proposed here that, out to at least $x \approx -22\ R_e$, these observed phenomena result from a mapping into the tail of the well-known substorm current wedge that is observed at synchronous orbit. Magnetic perturbations of the current wedge ought to be associated with a longitudinal distortion of the separatrix between open and closed magnetic field lines. Estimates based on observational evidence suggest that such a distortion can indeed account for tail phenomena during expansion phases, and that the distortion also maps along magnetic field lines to the auroral bulge that is observed in the ionosphere. The separatrix-distortion hypothesis thus provides a plausible and unifying explanation for expansion-phase phenomena observed in the auroral ionosphere, at synchronous orbit, and in the tail out to $x \approx -22\ R_e$.

I. Introduction

Substorms have different signatures in different regions of the magnetosphere. An important signature of the expansion phase is the plasma sheet thinnings often seen near onset out to $x \approx -22\ R_e$ (the apogee of ISEE) via the transit of satellites from the plasma sheet to the geomagnetic tail lobe [Hones et al., 1967; Dandouras et al., 1986]. Such observations [e.g., Hones et al., 1986] tend to show increased stretching of the magnetic field as the plasma sheet thins. Thinnings are typically followed by plasma sheet expansions later during a substorm [Hones et al., 1984]. In addition to the thinnings, dipolarization of the magnetic field has also been reported near expansion phase onset out to $x \approx -22\ R_e$ [Fairfield et al., 1981; Huang et al., 1991]. Huang et al. reported further that particle injections occur concurrently with the dipolarizations, and that these events have characteristics very similar to those observed at synchronous orbit. Such events were found by Huang et al. to be common in the tail within approximately 3 hours of magnetic midnight.

It seems that a complete description of substorm phenomenology for the tail should account for the approximately equal probabilities of observing either (a) plasma sheet thinning followed by plasma sheet expansion, or (b) dipolarization concurrent with particle injection near substorm onset within a few hours of midnight. Such a description should also account for plasma flows observed in the tail during substorms, which are occasionally outward as the plasma sheet thins but nearly always earthward as the plasma sheet expands [Hones et al., 1973; Lui et al., 1977a, b].

Thinnings, followed by expansions, of the plasma sheet are often interpreted in terms of the temporal evolution of a neutral line that forms earthward of $x \approx -22\ R_e$ at onset [e.g., McPherron, 1979; Hones et al., 1984]. However, this description does not explicitly include dipolarizations and concurrent particle injections as a common occurrence out to $x \approx -22\ R_e$.

In this paper, I consider the possibility that the tail phenomena described above are the direct result of an extension into the tail of the longitudinal structure of the substorm current wedge. This structure has been invoked to account for magnetic observations at synchronous orbit [e.g., Nagai, 1982, 1987] and has been proposed to be associated with the bulge in the auroral oval that forms in the ionosphere [Rostoker and Hughes, 1979; Tighe and Rostoker, 1981]. The interpretation of tail phenomena presented here depends upon the proposal [Lyons et al., 1990] that the longitudinal structure of the auroral bulge reflects a distortion of the separatrix between open and closed magnetic field lines, a distortion which is associated with the magnetic perturbations of the substorm current wedge.

II. Longitudinal Structure

Following the onset of a substorm expansion phase, a region of active aurora spreads poleward such that a portion of the aurora extends into the polar cap region previously devoid of aurora [Akasofu, 1964, 1977]. Images [Akasofu, 1977; Craven and Frank, 1985, 1987; Rostoker et al., 1987] show that the poleward

Magnetospheric Substorms
Geophysical Monograph 64

motion of a portion of the poleward boundary of the aurora often leads to a "bulge" in the auroral oval that protrudes into the polar cap. This bulge feature is illustrated by the solid curve in Figure 1, which is based on images presented in the above references. During the substorm growth phase, which precedes the expansion phase onset, the poleward boundary of the aurora is approximately circular, as illustrated by the dashed line in Figure 1.

The distinctive evolution of the poleward boundary, as determined from Viking satellite images [Anger et al., 1987] during the development of an auroral surge on September 24, 1986, is shown in Figure 2 [from Lyons et al., 1990]. The heavy, solid curves in Figure 2 were obtained by drawing smooth curves along the poleward boundary of identifiable aurora in each of a sequence of Viking images obtained approximately once per minute. For spatial reference, each panel in Figure 2 contains geographic coordinates, a bar identifying the magnetic meridian of the Sondrestrom radar in Greenland, a dot along the bar giving the location of the radar, and (for comparison with the later curves) a thin, solid line marking the poleward boundary of the aurora from an image taken 1 min prior to the sequence of heavy curves.

Figure 2 shows that, as the surge developed, the poleward boundary of the aurora moved poleward at longitudes east of the head of the surge and equatorward at longitudes west of the head of the surge. (The head of the surge, where the poleward boundary of the aurora assumes an approximately north-south orientation, was located slightly to the west of the Sondrestrom meridian in this case.) This motion of the poleward boundary gives a significant longitudinal distortion of the boundary, which leads to an auroral bulge of the sort illustrated by the expansion phase boundary in Figure 1. This distortion usually begins in a relatively narrow longitude sector and then expands both eastward and westward.

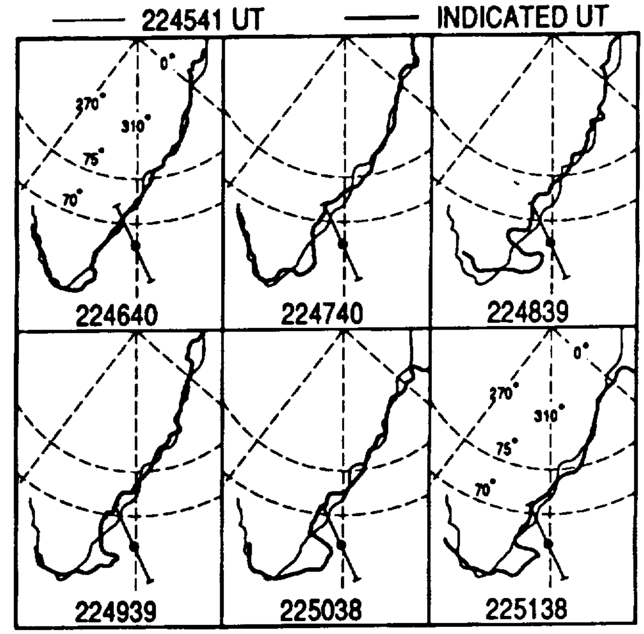

Fig. 2. Poleward boundary of identifiable aurora from a sequence of Viking images for September 24, 1986, obtained during a period of rapid development of an auroral surge near Sondrestrom. Geographic coordinates are used. The lighter curve in each panel is from an initial image for comparison with the boundary for the indicated UT. The bar identifies the field of view of the Sondrestrom radar along its magnetic meridian, and the open circle on the bar gives the radar location.

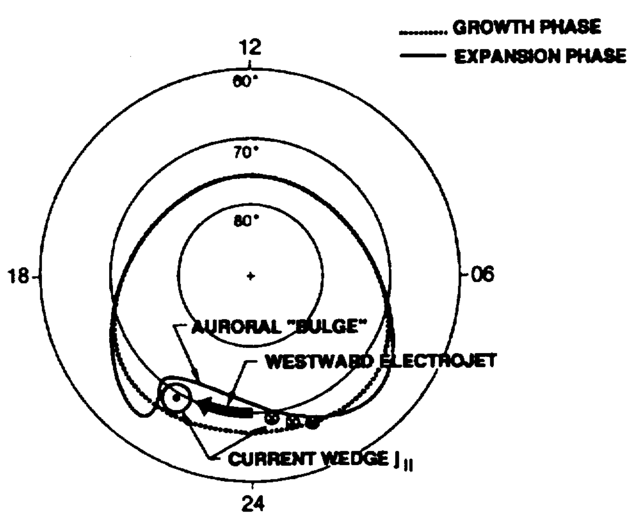

Fig. 1 Sketch of the poleward boundary of the auroral oval at times during the growth phase of a substorm (just prior to expansion phase onset) and during the expansion phase. The spatial relation of the auroral bulge to the field-aligned wedge currents $j_\parallel$ and westward electrojet is also illustrated for the expansion phase

If it is assumed that the poleward boundary of the aurora lies along, or adjacent to, the separatrix between open and closed magnetic field lines, then the development of an auroral bulge must be associated with a corresponding distortion of the separatrix. This same assumption was used by Craven and Frank [1987] and Frank and Craven [1988] to estimate variations in the area of open, polar cap field lines during substorms. It is not necessary that the poleward boundary of the aurora lie precisely at the separatrix for the inferred distortion of the separatrix to be valid, but it is necessary that the boundary lie near the separatrix and that the shape of the boundary approximate that of the separatrix.

The western portion of an auroral bulge typically contains at least one azimuthally localized surge having enhanced upward field-aligned currents and auroral intensity. The field-aligned current associated with a surge [Inhester et al., 1981; Opgenoorth et al., 1983] is believed [Rostoker and Hughes, 1979; Tighe and Rostoker, 1981] to be the dusk portion of the substorm current wedge that develops during a substorm expansion phase [McPherron, 1973; Baumjohann, 1983]. The current-wedge includes an enhanced westward electrojet in the ionosphere that connects downward field-aligned currents to the east and upward field-aligned currents to the west. The relation of the auroral bulge to the westward electrojet and the field-aligned currents of the wedge is illustrated in Figure 1 for the idealized case of a single surge near the western edge of the bulge region.

As illustrated in Figure 1, the distortion of the poleward boundary of the aurora at the edges of the auroral bulge occurs in the region of the wedge field-aligned currents. These field-aligned currents map along magnetic field lines into the magnetosphere, and their magnetic effects are readily observable in the vicinity of synchronous orbit [e.g., Nagai, 1982, 1987].

Magnetic field lines in the tail become stretched away from the Earth during a substorm growth phase. This stretching is particularly dramatic at synchronous orbit, where its signature is an increase in the magnitude of B_x and a decrease in the magnitude of B_z (GSE coordinates). At expansion phase onset, the magnetic field at synchronous altitude returns to a more dipolar orientation within the longitude range spanned by the current wedge. This reconfiguration is observed to begin in a relatively narrow longitude sector near midnight and to then expand both eastward and westward [Arnoldy and Moore, 1983], as does the auroral bulge. Particle injections are observed to accompany this "dipolarization" of the magnetic field [Moore et al., 1981; Nagai 1982].

During an expansion phase, the current wedge expands in longitude along with the magnetic field dipolarization. The occurrence of dipolarization at any particular longitude coincides with the passage of the current wedge across that longitude. Such a passage of the current wedge is identifiable by B_y perturbations at the time of dipolarization. The magnetic perturbation is northward at longitudes within the current wedge, which changes the field to an orientation that appears more nearly dipolar. Outside the current wedge, however, the magnetic field perturbation is southward. This causes an increased stretching of the field. Such stretching of the field outside the current wedge after expansion phase onset has been observed by Nagai [1982, 1987] and by Arnoldy and Moore [1983]. Gelpi et al. [1987] compared the post-onset longitudes of stretching and dipolarization at synchronous orbit to the longitudes of surges observed on the ground. They found that the stretching occurred west of the head of the surge and that the dipolarization occurred east of the head of the surge, as is expected if the upward field-aligned currents were located near the head of the surge, as illustrated in Figure 1.

III. Extension to the Tail: Separatrix-Distortion Hypothesis

Assuming that wedge currents extend into the tail to distances well beyond synchronous orbit, their magnetic effects ought to be observable at such distances as well as near synchronous orbit. In fact, Rostoker and Eastman [1987] and Eastman et al. [1988] have reported clear magnetic signatures, which they attribute to the current wedge, from ISEE at $x = -15\,R_e$ to $-22\,R_e$ in the tail. This offers a simple explanation for the magnetic field dipolarizations observed in the tail at substorm onset. Such dipolarizations would be expected to occur at longitudes within the current wedge that forms at onset. Plasma sheet thinnings, which are also observed in tail, would thus be expected at longitudes outside the current wedge. Under this scenario, the "dipolarizations" would not actually be a dipolarization of the entire magnetic field at longitudes within the current wedge unless the northward B_z perturbation reduced the total cross-tail current. However, the field would turn to a more dipolar orientation at an observation location within the plasma sheet.

The changes in the magnetic field component approximately normal to the cross-tail current sheet found by Huang et al. [1991] after onset were $\Delta B_z \sim 5 - 10$ nT. Such perturbations can be attributed to field-aligned currents $\sim 10^5$A [Lyons, 1991] if the outward and earthward field-aligned components of the current wedge are assumed to be separated by $\sim 2.5\,R_e$. The Tsyganenko [1987] model maps $\Delta y = 2.5\,R_e$ across the tail at $x = -15$ to $-22\,R_e$ to $\Delta y \approx 1.25\,R_e$ at $x = -6.6\,R_e$ and to $\Delta y \approx 750$ km in longitude in the auroral ionosphere [H. Spence, private communication, 1990]. The reduction in Δy by a factor of ~ 2 between the tail and synchronous orbit suggests that ΔB_z would be $\sim 10 - 20$ nT at synchronous orbit if the field-aligned current magnitude were the same there as in the tail. However, observations of Nagai [1987], which show that ΔB_z is $\sim 30 - 40$ nT at synchronous orbit, suggest that part of the field-aligned wedge current closes at radial distances closer to the Earth than $15\,R_e$. Nevertheless, a significant portion of the wedge current appears to extend well out into the tail.

Figure 3 shows a cross section of the geomagnetic tail and includes arrows which illustrate the magnetic perturbations from the field-aligned wedge currents. As illustrated, the ΔB_z perturbations are perpendicular to the cross-tail current sheet. This ΔB_z should lead to an increase in closed magnetic flux at longitudes spanned by the current wedge and to a decrease in closed magnetic flux at longitudes outside the wedge. Thus, as the current wedge forms during the substorm expansion phase, the separatrix between open and closed magnetic field lines should develop a bulge at longitudes within the wedge, as illustrated by the expansion phase separatrix in Figure 3. Such a change in the distribution of closed flux in the tail should develop along with the formation of the current wedge.

A distortion of the separatrix in the tail, as illustrated in Figure 3, will map along field lines to the auroral ionosphere and produce a poleward protruding bulge at longitudes within the current wedge. The amplitude of the bulge can simply be estimated from flux conservation. Let us assume that the $\Delta B_z = 10$ nT across the midplane of the tail within the current wedge, and that this ΔB_z extends over a $50\,R_e^2$ area ($\Delta y = 2.5\,R_e$ and $\Delta x = 20\,R_e$). This gives an additional closed magnetic flux $\Delta\Phi = 500$ nT R_e^2 within the current wedge. Since the vertical component of B in the auroral ionosphere is about 5×10^{-5} T, the area of the bulge there must be about $10^{-2}\,R_e^2$ ($\approx 4 \times 10^5$ km^2). Using the mapping of $\Delta y = 2.5\,R_e$ in the tail to 750 km in longitudinal extent in the ionosphere obtained from the Tsyganenko [1987] model, we obtain that the auroral bulge ought to extend about 540 km ($\sim 5°$ in latitude) poleward of the poleward boundary of the growth phase auroral oval. This is reasonable protrusion into the polar cap for an auroral bulge.

The simple calculation above ignores B_y effects and the opening of field lines at longitudes outside the current wedge (which should be responsible for the equatorward motion of the poleward boundary of the aurora outside the current wedge); however, these corrections should be factor of ~ 2 corrections.

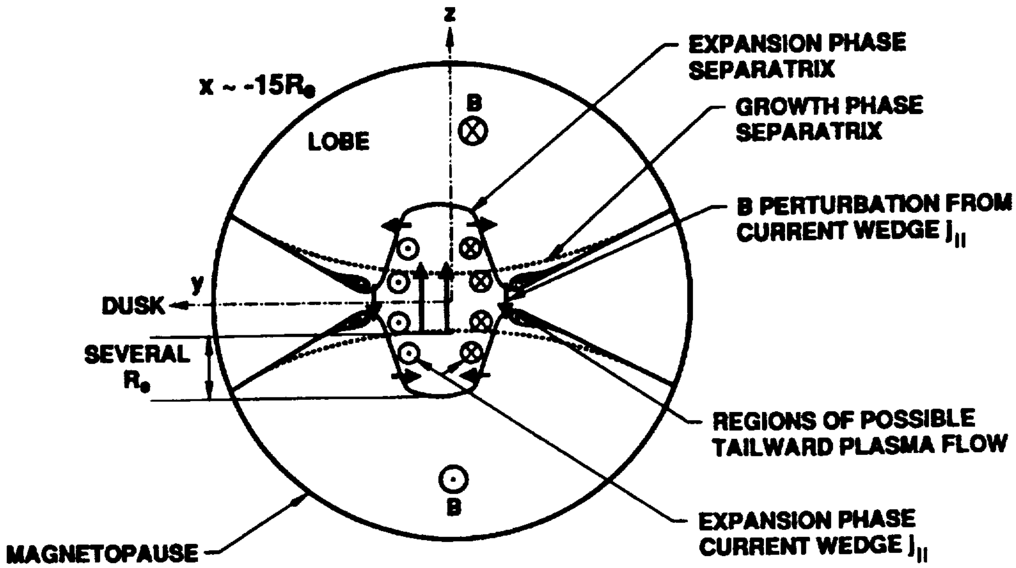

Fig. 3. Illustration of phenomena predicted to occur in the tail in association with the formation of the substorm current wedge.

Also, three-dimensional evaluations of magnetic field distortion by the current wedge have been performed by Vasil'ev et al. [1986], and they obtained ionospheric mappings of the distortion that appear realistic for surges. Thus, it appears that the magnetic perturbations produced by the wedge currents can close sufficient flux to account for the auroral bulge.

A simple calculation can also be performed to estimate the extent to which the distorted separatrix extends into the lobes of the tail. At a distance ($\sim 15\ R_e$) beyond which about one-half of the wedge-produced flux $\Delta\Phi$ closes across the midplane of the tail, the portion of the distorted separatrix that extends into each of the growth phase lobe regions must enclose ~ 250 nT R_e^2 of magnetic flux. By taking B_x to be 20 nT in the lobes and by taking $\Delta y = 2.5\ R_e$ as before, we find that the separatrix must extend $\sim 5\ R_e$ into each of the pre-existing lobes. If the region of newly closed field lines becomes filled with plasma sheet plasma, we should expect an $\sim 10\ R_e$ expansion of the total width of the plasma sheet in the z-direction at longitudes within the current wedge. We should further expect a significant thinning of the plasma sheet outside the current wedge. Both the expected expansion and the expected thinning of the plasma sheet during the substorm expansion phase are illustrated in Figure 3. The current wedge and associated distortion of the separatrix should expand in both the +y and −y directions as the expansion phase progresses.

IV. Interpretation of Tail Observations in Terms of Separatrix Distortion

The distortion of the separatrix illustrated in Figure 3 represents an extension of the known longitudinal structure of the current wedge and auroral surge into the tail, and it offers a possible description of phenomena observed in the tail during the substorm expansion phase.

At longitudes spanned by the current wedge that forms at expansion phase onset, the magnetic field should appear to dipolarize and the induced electric field associated with the dipolarization should energize trapped particles. Satellites within the plasma sheet and the longitude range of the current wedge at onset should thus observe magnetic field dipolarization and concurrent dispersionless injections. Such events should be similar to those observed at synchronous orbit. The observations of Huang et al. [1991] are consistent with these expectations.

At longitudes outside the current wedge, the plasma sheet should first thin as the amount of closed flux decreases. Thinning should be observed close to the time of onset if the spacecraft longitude is sufficiently near (within a few R_e of) the current wedge. It should be observed later during the expansion phase at more distant longitudes. This latter expectation is consistent with the recently reported ISEE observation [Hones et al., 1990] that a tail plasma sheet thinning observed at 0130 MLT occurred 20 min after the onset of a substorm on May 4, 1986. Thinning should lead occasionally to a very thin plasma sheet outside the current wedge after onset. Indeed, very thin cross-tail current sheets (~ 400 km) have been reported by McPherron et al. [1987] and Mitchell et al. [1990] to occur after onset but prior to dipolarization in the near-Earth tail ($x \approx -12\ R_e$). Particle data obtained during the time of the observations of Mitchell et al. indicate that the thin current sheet had developed to the east of the expansion phase current wedge [Williams et al., 1990].

Following the thinning of the plasma sheet at any particular longitude, the plasma sheet should expand in z as the field-aligned current of the current wedge moves across that longitude. This scenario is consistent with the observation that the tail plasma sheet thins and then expands after expansion phase onset.

The present model may also account for outward flowing plasma at the edge of the rapidly thinning plasma sheet. Outside the current wedge, the ionospheric mapping of the separatrix between open and closed field lines moves equatorward in response to the decrease in B_z across the midplane of the tail. If the separatrix moves equatorward faster than does the convecting plasma, then the separatrix will overtake the convecting plasma, thereby transferring plasma from closed field lines to open field lines [Lyons et al., 1989]. Such a transfer of plasma can be visualized as "reverse reconnection." It would require that the induced electric field exceed the convection electric field at the tail magnetic X-line, so that $E \cdot J < 0$ there [Vasyliunas, 1984]. Even without this, longitudinal drift in the tail could carry energetic particles across the distorted separatrix and lead to their appearance as bursts of flowing particles on open field lines.

The plasma and/or energetic particles transferred to open field lines will be lost from the magnetosphere by flowing outward along open field lines that lie adjacent to the separatrix, as illustrated by the small shaded regions in Figure 4. Such outward plasmas flows should occur only as the plasma sheet in the tail thins and not as it expands. Flows observed at the outer boundary of the plasma sheet [Hones et al., 1973; Lui et al., 1977a, b] are consistent with this prediction. Also, the observations in Figure 2 show that rapid equatorward motion of the poleward boundary of the aurora occurred just to the west of the head of the developing surge, which was located near the Sondrestrom radar. The boundary moved equatorward by about 250 km between 2245:41 UT and 2248:39 UT, which corresponds to a speed of ~1.4 km/s, which was considerably faster than the equatorward plasma drift measured by the radar along the radar magnetic meridian at approximately the same time [Lyons et al., 1990]. We thus presume that plasma was transferred from closed to open field lines over this longitude range at that time, which would have lead to outward plasma flows in the tail.

The above discussion provides an interpretation of general tail phenomena observed during substorm expansion phases in terms of the separatrix-distortion hypothesis. It thus provides a means for re-interpreting detailed sets of data that have been obtained in the tail during specific expansion phase events and interpreted in terms of the temporal formation and movement of a near-Earth neutral line. It would be profitable to reexamine such data to see whether they can be interpreted alternatively (or better) in terms of separatrix distortion. Here, I consider two such data sets.

April 24, 1979

A substorm having an onset between 1111 UT [Eastman et al., 1988] and 1112 UT [Hones et al., 1986] on April 24, 1979, (CDAW 7) has been the subject of several papers. Figure 4, from Hones et al., shows ISEE 2 magnetic field, ion pressure, and ion flow data for a time interval that includes the substorm. Following onset, the ion pressure first went up, and then decreased below the level of detectability by about 1116 UT as the satellite went into the lobe. The satellite reentered the plasma sheet just after 1140 UT. The exit of the satellite from the plasma sheet was presumably the result of plasma sheet thinning, and the return of the plasma sheet to the satellite was presumably the result of plasma sheet expansion. Plasma flow was outward at the outer boundary of the thinning plasma sheet and earthward at the outer boundary of the expanding plasma sheet. According to the interpretation of Hones et al., a neutral line had formed earthward of the satellite at substorm onset so as to produce the plasma sheet thinning and associated outward flows. The later expansion of the plasma sheet was interpreted as the result of a tailward retreat of the neutral line.

However, the observations in Figure 4 are equally consistent with the separatrix distortion hypothesis. The satellite was at $y \sim 5\ R_e$, and thus could reasonably have been west of the current wedge that formed at onset. Consistent with this expectation, B_z went negative as the plasma sheet thinned soon after onset. This is what would be expected from the opening of field lines west of the current wedge. The plasma sheet appears to have thinned rapidly and thus could have left previously trapped plasma on freshly opened field lines. This interpretation would account for the outward flows associated with the plasma sheet thinning in Figure 4. (At the end of the period of outward flow,

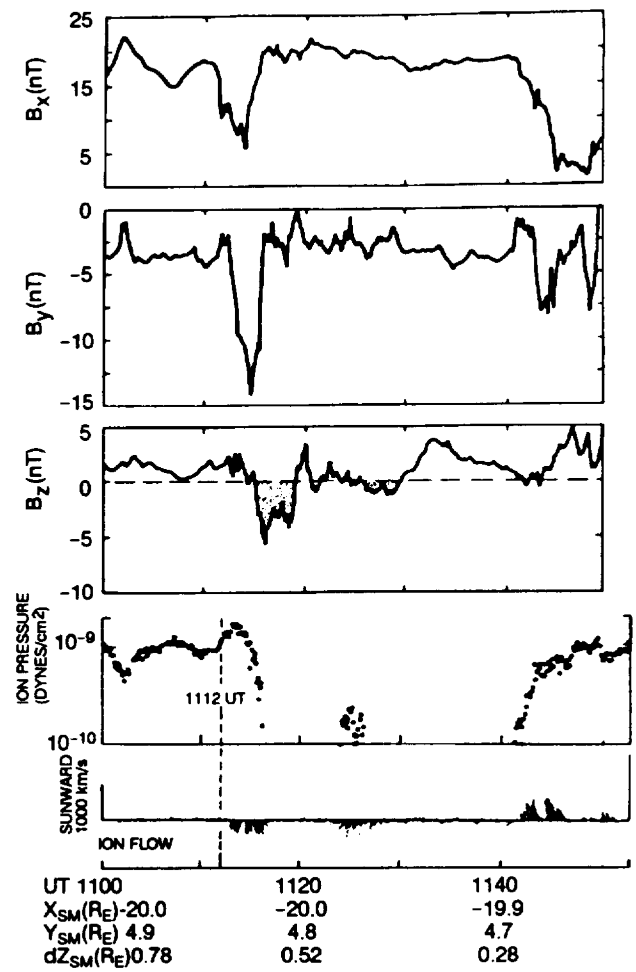

Fig. 4. Magnetic field, ion pressure, and ion flow data obtained from ISEE 2 during a substorm on April 24, 1979. Expansion phase onset (1112 UT) is indicated. The satellite position is given along the bottom of the figure, where dZ is the distance above an estimated position of the tail current sheet (from Hones et al. [1986]).

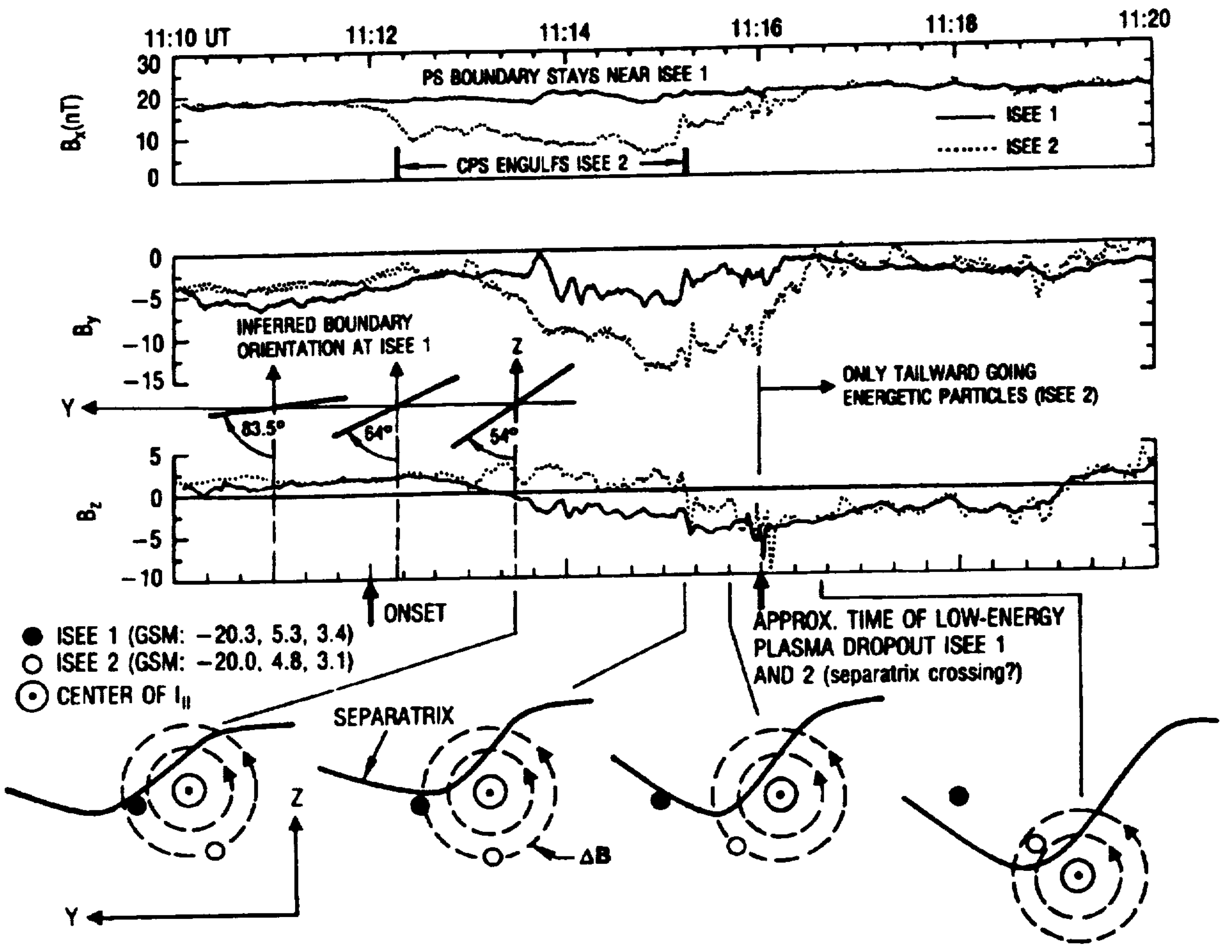

Fig. 5. Observations from a 10 min interval that includes the times of onset and plasma sheet thinning of the April 24, 1979, substorm. Simultaneous ISEE 1 and ISEE 2 magnetometer data, as well as the orientations of the outer boundary of the plasma sheet in the y,z plane, are from Kettmann et al. [1990]. Approximate time of the dropout of plasma sheet particles are from Figures 6 and 8 of Hones et al. [1986]. Both Hones et al. and Kettmann et al. found outward-going energetic particles for a time after 1116 UT on ISEE 2. Locations of the two spacecraft in the y,z-plane, relative to the center of the outward field-aligned current distribution, are based sed on Eastman et al. [1988]. Separatrix configurations and locations are based on the separatrix-distortion hypothesis. In both the boundary orientation and the spacecraft location diagrams, dusk (positive y) is to the left.

during the interval 1116:00 to 1116:30 UT, there were no observable earthward going ions [see Figure 9 of Hones et al., 1986]; this is difficult to explain solely in terms of the boundary layer dynamics model of Rostoker and Eastman [1987]). The B_y perturbation near onset suggests that the satellite was located quite near the initial location of the field-aligned currents.

Expansion of the plasma sheet in z about 25 min later can be seen to have been accompanied by a positive change in B_z and a significant B_y perturbation. This is consistent with the passage of the outward field-aligned wedge current across the longitude of the satellite at that time. Earthward flow is observed along the outer boundary of the expanding plasma sheet, as would be expected for the usual plasma sheet boundary layer [Eastman et al., 1984]. This flow most likely resulted from interactions with the distant cross-tail current sheet [Lyons and Speiser, 1982].

Figure 5 summarizes observations from a 10 min interval that includes the time of plasma sheet thinning. The simultaneous ISEE 1 (solid curve) and ISEE 2 (dashed curve) magnetic field data and the orientations of the outer boundary of the plasma sheet in the y,z plane (as inferred from ISEE 1 energetic particle observations) are from Kettmann et al. [1990]. The approximate time of the dropout of plasma sheet particles on ISEE 1 and 2 was obtained from Figures 6 and 8 of Hones et al. [1986]. Both Hones et al. and Kettmann et al. found outward-going energetic particles after 1116 UT at ISEE 2. The diagrams at the bottom of Figure 5 show the locations of the two spacecraft in the y,z plane relative to the center of the outward field-aligned current distribution. These locations are based on the analysis of Eastman et al. [1988]. The separatrix locations and configurations in the diagrams are based on the separatrix distortion hypothesis discussed here. Dusk (positive y) is to the left in both the boundary orientation and the spacecraft location diagrams.

At ISEE 1, B_x remained approximately at its lobe value throughout the entire time interval included in Figure 5. This implies that ISEE 1 remained near the outer boundary of the plasma sheet until about 1116 UT, when it entered the lobe. Consistent with this interpretation, earthward plasma flows typical of the plasma sheet boundary layer were observed on ISEE 1 during the interval 1111-1113 UT [see Figure 13 of Eastman et al., 1988]. Before the substorm onset, ISEE 2 was also near the plasma sheet boundary; however, after onset, ISEE 2 went further into the plasma sheet for a few minutes, as indicated by the increase in plasma pressure [Hones et al., 1986] and concurrent decrease in B_x.

Figure 5 shows that after onset, B_z remained positive at ISEE 2, but decreased and became negative by about 1113 UT at ISEE 1. Also By became increasingly negative at ISEE 2 but remained approximately constant at ISEE 1. These observations suggest that the outward field-aligned current at onset was centered at a longitude between the two spacecraft and at about the same z value as ISEE 1. This position is shown in the leftmost diagram at the bottom of Figure 5. The B_z perturbation associated with the wedge current is expected to have closed field lines at the longitude of ISEE 2 but to have opened field lines at the longitude of ISEE 1. Thus, the magnetic separatrix should have moved closer to ISEE 1 after onset, but should have moved farther above ISEE 2. These motions would have distorted the magnetic separatrix in the manner shown in the diagram. In particular, the separatrix should have sloped towards positive z with decreasing y in the vicinity of the outward wedge current at this time (~1112 -1115 UT). This is opposite to the slope normally expected on the dusk side of midnight. Kettmann et al. [1990] inferred the orientation of the outer boundary of the plasma sheet for times just after onset. As is shown near the middle of Figure 5, the inferred boundary orientations have the same unexpected slope as predicted by the separatrix distortion hypothesis!

A few minutes after onset (about 1115 UT), B_z also became negative at ISEE 2. Eastman et al. [1988] interpreted this to mean that the center of the outward wedge current moved towards the midnight meridian (opposite to the expected direction), as sketched in the middle two diagrams at the bottom of Figure 5. As this movement occurred, the plasma sheet would be expected to thin at the longitude of ISEE 2. Consistent with this expectation, B_x goes up and the plasma pressure goes down [Hones et al., 1986] at ISEE 2 soon after B_z becomes negative. Thinning of the plasma sheet continued after this time at least until ~1116 UT, when both spacecraft entered the lobe. At ISEE 2, tailward-going energetic particles are seen for a few minutes following 1116 UT, as if the rapid opening of field lines had left some particles on freshly opened field lines.

The above discussion suggests that the detailed observations around the time of onset of the substorm on April 24, 1979, can be understood clearly in terms of the separatrix-distortion hypothesis.

May 3, 1986

Another substorm that has been studied in detail is one with an onset at 0919 UT on May 3, 1986 (CDAW 9). Ground based magnetograms from Alaska, together with magnetic field and 6 keV electron data from ISEE 1 for the period 0900 UT to 1030 UT (from Hones et al. [1987]) are shown in Figure 6. Hones et al. suggested that a new neutral line had formed just tailward of ISEE 1 at onset, and that this neutral line had begun to retreat tailward at 1003 UT. However, the data shown in Figure 6 are also consistent with the separatrix-distortion hypothesis.

The H-component magnetogram data in Figure 6 show that electrojet activity began near the onset time at about 65° geomagnetic latitude. Activity then moved poleward, and multiple particle injections (at 0919, 1936, and 0942 UT) were seen in synchronous orbit data presented by Hones et al. [1987]. While electrojet activity at lower latitudes decreased after about 0953 UT, activity at 71° latitude continued to increase, especially after 1003 UT.

During this time interval, ISEE 1 was located 3.5 R_e west of midnight, and the 6 keV electron data indicate that the plasma sheet gradually thinned at that location from 0920 to 0930 UT. This thinning would be expected if ISEE were well to the west of the expanding substorm current wedge. The measured B_z de-

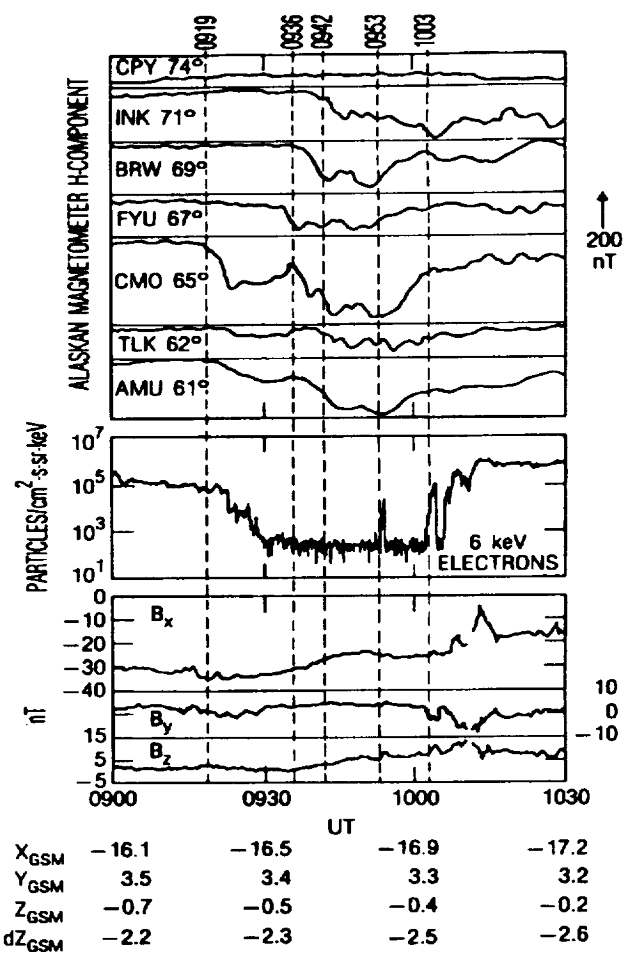

Fig. 6. Ground-based magnetogram data and ISEE 1 magnetic field and 6-keV electron data for the period of the substorm on May 3, 1986 (from Hones et al. [1987]).

creased very slightly during this period of time; however, it is difficult to determine whether this decrease is significant. Later, the plasma sheet expanded in z back over ISEE 1, initially between 1002 UT and 1004 UT, and finally during the period 1006 UT to 1012 UT. During these two time intervals, the magnetic field data at ISEE showed positive B_z and negative B_y perturbations. This is consistent with what would be expected if the current wedge had expanded irregularly across the longitude of ISEE 1 during this time period.

Viking images of the aurora are available for this substorm period, starting at 0930:19 UT (see Figure 3 of Hones et al. [1987]), and Hones et al. [1990] found a very interesting association between the auroral evolution and the expansion of the plasma sheet. They noted that an auroral surge intensified and moved westward from 1003 UT to 1009 UT. This time interval corresponds to the time of enhanced electrojet activity at 71° latitude mentioned above. The surge was located between 70° and 75° invariant latitude, and field line mapping performed by Hones et al. [1990] suggests that the surge moved westward across the field line of ISEE 1 at about the time that the plasma sheet expansion was observed. This is just what is expected if the current wedge, and thus the associated distortion of the separatrix and poleward boundary of the aurora, moved across the longitude of ISEE during this time period.

The above association between an auroral surge observed in the ionosphere and the plasma sheet expansion and B_z changes at ISEE are essentially the same as the association observed at synchronous orbit by Gelpi et al. [1987] between auroral surges and the substorm current wedge. This supports the hypothesis that substorm phenomena observed in the tail out to at least $x \approx -22\,R_e$ result from the extension into the tail of the longitudinal structure associated with the current wedge that is observed at synchronous orbit and in the auroral zone.

V. CONCLUSIONS

Tail phenomena that occur out to at least $x \approx -22\,R_e$ during the expansion phases of substorms, previously interpreted in terms of a near-Earth neutral line that forms at onset and later moves outward, can be understood alternatively in terms of a distortion of the magnetic separatrix by the substorm wedge current. Moreover, the auroral bulge that develops during a substorm expansion phase can be understood as the ionospheric mapping of the distorted separatrix [Lyons et al., 1990]. Since distortion of the separatrix should result from magnetic perturbations associated with the wedge currents, the distortion should expand in longitude as the current wedge expands. A significant portion of the field-aligned wedge current must extend out to at least $x \approx -22\,R_e$ under this hypothesis, though part of the wedge current may well close nearer than this to the Earth.

The separatrix-distortion hypothesis accounts for the approximately equal probabilities of observing magnetic field "dipolarization" accompanied by particle injection and of observing plasma sheet thinning followed by plasma sheet expansion. Either phenomena may occur near substorm expansion phase onset within a few hours of midnight. Field dipolarization and concurrent particle injection are expected to occur at longitudes spanned by the current wedge that forms at onset. Thinnings, which should be accompanied by enhanced stretching of the magnetic field and perhaps by negative B_z, should be observed outside the current wedge. Since the current wedge expands in longitude with time, thinnings should be followed by dipolarizations and concurrent plasma sheet expansions. Thinnings may be observed near the time of onset at longitudes near the initial range spanned by the current wedge. However, both thinnings and expansions should be increasingly delayed relative to onset with increasing longitudinal displacement from the initial location of the current wedge.

Outward plasma flows can also be explained within the context of the separatrix-distortion hypothesis. Such flows would be expected to develop if closed field lines containing trapped plasma become open at a rate faster than the rate at which plasma is convected towards lower latitudes. This would allow previously trapped plasma to escape the tail along freshly open field lines. Even if this condition for outward plasma flow were not met, longitudinal drift in the tail could carry energetic particles across the distorted separatrix and lead to their appearance as bursts of particles flowing outwards along open field lines.

Separatrix distortion offers a unifying explanation for expansion phase phenomena observed in the auroral ionosphere, at synchronous orbit, and in the tail out to at least $x \approx -22\,R_e$. The cause of expansion phase onset has not been considered here, but the separatrix-distortion hypothesis may well be compatible with proposed causes, such as enhanced reconnection associated with the formation of a neutral line somewhere in the tail [Coroniti, 1985], instability arising from magnetosphere-ionosphere coupling processes [Kan and Kamide, 1985; Rothwell et al., 1986], and thermal catastrophe [Goertz and Smith, 1989]. To be consistent with the separatrix-distortion hypothesis discussed here, neutral line formation at substorm onset would have to occur either outside the longitude range spanned by the current wedge or beyond $x \approx -22\,R_e$.

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